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THE FIRST VLBI DETECTION OF AN ULTRACOOL DWARF: IMPLICATIONS FOR THE DETECTABILITY OF SUB-STELLAR COMPANIONS

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ABSTRACT

We present milliarcsecond-resolution radio very long baseline interferometry (VLBI) observations of the ultracool dwarfs TVLM 513–46546 (M8.5) and 2MASS J00361617+1821104 (L3.5) in an attempt to detect sub-stellar companions via direct imaging or reflex motion. Both objects are known radio emitters with strong evidence for periodic emission on timescales of about 2 and 3 hours, respectively. Using the inner seven VLBA antennas, we detect unresolved emission from TVLM 513–46546 on a scale of 2.5 mas ($\sim$ 50 stellar radii), leading to a direct limit on the radio emission brightness temperature of $T_B \gtrsim 4 \times 10^5$ K. However, with the higher spatial resolution afforded by the full VLBA we find that the source appears to be marginally and asymmetrically resolved at a low S/N ratio, possibly indicating that TVLM 513–46546 is a binary with a projected separation of $\sim$ 1 mas ($\sim$ 20 stellar radii). Using the 7-hr baseline of our observation we find no astrometric shift in the position of TVLM 513–46546, with a 3σ limit of about 0.6 mas. This is about 3 times larger than expected for an equal mass companion with a few-hour orbital period. Future monitoring of its position on a range of timescales will provide the required astrometric sensitivity to detect a planetary companion with a mass of $\sim$ 10 M_J in a $\gtrsim$ 15 d ($\gtrsim$ 0.06 AU) orbit, or with a mass of $\sim$ 2 M_J in an orbit of $\gtrsim$ 0.5 yr ($\gtrsim$ 0.3 AU).

Subject headings: stars: low-mass, brown dwarfs – radio continuum: stars

1. INTRODUCTION

In recent years unexpectedly strong radio emission has been detected from very low mass stars and brown dwarfs (hereafter, ultracool dwarfs), revealing that these objects are capable of generating and dissipating kG-strength magnetic fields (e.g., Berger et al. 2001; Berger 2006; Hallinan et al. 2008). The radio luminosity remains nearly uniform from early-M to mid-L dwarfs, even though other magnetic activity indicators (Hα and X-rays) decline by about two orders of magnitude over the same spectral type range (e.g., West et al. 2004; Berger 2006). Thus, radio observations provide a particularly powerful probe of the magnetic field properties.

The radio emission from several ultracool dwarfs also exhibits a periodicity that matches the stellar rotation velocity ($v\sin i$), thereby pointing to a large-scale, axisymmetric, and stable magnetic field configuration on timescales of hours to years (Berger et al. 2005; Hallinan et al. 2006, 2007; Berger et al. 2009). These conclusions are also supported by observations of Zeeman broadening in FeH molecular lines (Reiners & Basri 2007) and time-resolved optical spectropolarimetry (Donati et al. 2008; Morin et al. 2008).

Since ultracool dwarfs are fully convective, the solar-type $\alpha\Omega$ dynamo, which operates at the shearing interface between the radiative and convective zones (Parker 1955), cannot be responsible for generating and amplifying the inferred fields. However, recent numerical simulations suggest that large scale axisymmetric fields can still be generated in fully convective objects, at least for conditions that roughly correspond to mid-M dwarfs ($M \sim 0.3$ M$_\odot$; Browning 2008). Simulations that correspond to the conditions in ultracool dwarfs are challenging and have not been investigated so far. As a result, observational constraints on the scale, geometry, and origin of the fields are essential. The spectroscopic Zeeman techniques are currently of limited utility for the dim and generally rapidly-rotating ultracool dwarfs, since they require very high signal-to-noise ratios and have reduced sensitivity at high rotation velocities due to line broadening (Reiners & Basri 2007). Detailed radio observations are thus crucial.

Here we present the first very long baseline interferometry (VLBI) observations of ultracool dwarfs, aimed at providing further constraints on their magnetic field properties. In particular, these observations have sufficient angular resolution to detect astrometric shifts of a few tenths of a milliarcsecond that may be exerted by a sub-stellar companion with a period of a few hours. They also allow us to directly image a radio-emitting companion down to milliarcsecond scales. The presence of such putative companions may enhance the magnetic activity through direct or tidal interaction. We detect the well-studied M8.5 dwarf TVLM 513-46546 with the VLBA, the first such detection for any ultracool dwarf. The detectability of this object with the VLBA suggests that long-term astrometric monitoring could reveal the presence of a planetary-mass companion on a $\gtrsim$ 15 d orbit. Such a detection would also usher in a new era of extrasolar planet studies through radio astrometry.

2. TARGETS AND OBSERVATIONS

The M8.5 dwarf TVLM 513–46546 (hereafter TVLM513–46) is located at a distance of 10.6 pc (Dahn et al. 2002). It was first detected at radio wavelengths by Berger (2002) who found persistent emission and a circularly polarized flare lasting about 15 min at 8.5 GHz. Subsequently, Osten et al. (2006) detected quiescent radio emission at 4.9 and 8.5 GHz, but did not detect any flares. Hallinan et al. (2006) found rotational modulation in the radio emission with a periodicity of $\sim$ 2 hr, and subsequently, Hallinan et al. (2007) detected periodic bursts of circularly polarized radio emission with a period of 1.96 hr. Most recently, Berger et al. (2008) confirmed the presence of polarized flares combined with quiescent emission in simultaneous multi-wavelength observations (radio, X-ray, and Hα). These authors also found weak X-ray

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emission and periodic Hα emission. Thus, the current picture of the radio emission from TVLM513–46 is one involving different activity states; quiescent radio emission appears to always be present ($200-400$ μJy at 8.5 GHz), but variability and periodic bursts have not been detected in all observations.

We also observed 2MASS J00361617+1821104 (hereafter, 2M0036+18), an L3.5 dwarf located at a distance of 8.8 pc (Dahn et al. 2002). This object has also been previously detected at radio wavelengths: Berger et al. (2005) found strongly variable and periodic radio emission with a periodicity of 3 hr, which was later confirmed by Hallinan et al. (2008). The average 8.5 GHz flux density measured previously was about 135 μJy (Berger et al. 2005).

2.1. *Radio Observations*

TVLM513–46 and 2M0036+18 were observed simultaneously with the Very Long Baseline Array (VLBA), the Very Large Array (VLA), and the Green Bank Telescope (GBT) on 2008 March 30. Four hours of on-source time in the VLBI observations were obtained at 05:45–12:32 UT for TVLM513–46 and 13:40–20:35 UT for 2M0036+18; the VLA observations covered the entire time range. All data were analyzed with the Astronomical Image Processing System (AIPS).

2.1.1. *VLA*

VLA observations were obtained at a frequency of 8.5 GHz with 26 antennas in the C configuration. We used the standard continuum setup with 2×50 MHz bands and full polarization. Flux calibration was obtained using J1331+305, while J1455+2131 (for TVLM513–46) and J0019+2021 (for 2M0036+18) were used as complex gain calibrator sources. The bootstrapped flux densities for these two sources were 0.081 Jy and 0.866 Jy, respectively. About once every 50 min additional scans of secondary calibrators were obtained, resulting in corresponding gaps in the target source light curves.

2.1.2. *VLBA+VLA+GBT*

The VLBI observations included the 10-antenna VLBA, the GBT, and the VLA as a phased array. Phase-referenced observations were carried out with a data rate of 256 Mbit s^{-1} in dual polarization, using 2-bit sampling. Eight base-band channels of 8 MHz bandwidth each covered an aggregate bandwidth of 32 MHz. The correlator dump time was 2 s. The complex gain calibrators J1455+2131 and J0019+2021 were located at distances of 1.8° and 4.4°, respectively.

Unfortunately, the phase calibrators were not sufficiently bright to phase up the VLA between scans on the target sources, and the phased VLA data had to be removed from the VLBI experiment. Similarly, the GBT experienced bad weather, and the telescope had to be stowed for nearly 2.5 hr due to freezing rain during the second half of the experiment. As a result of the poor phases we also removed the GBT from the VLBI experiment. Finally, of the ten VLBA antennas, we removed Hancock (Hn), which experienced heavy snow fall and hence elevated system temperatures. We therefore separately analyze the VLA and VLBA data sets.

3. RESULTS

The VLA data allow us to determine the flux densities of our target sources, to construct light curves, and to constrain the search areas for counterparts on VLBI scales.

3.1. *VLA observations*

Both sources are detected in the VLA observations. TVLM513–46 has a flux density of 539 ± 19 μJy, and is located at a position of RA=15$^{\rm h}$01$^{\rm m}$08.162$^{\rm s}$ ($\pm$0.002 s), Dec=+22°50′01.673″ ($\pm$0.035″). The synthesized beam size is $2.3'' \times 2.2''$. No circular polarization is detected in the integrated data, with a 3σ limit of $r_c \lesssim 9\%$. The light curve reveals that the emission is composed of a quiescent component and short-duration flares lasting for only a few minutes but with circular polarization approaching $\sim 100\%$ (Figure 1). The most prominent flares are detected at 08:25 and 09:22 UT. During the first two hours, when no flares are detected, the flux density is 445 ± 28 μJy.

In light of previous results indicating that TVLM513–46 exhibits periodic radio variability, we conducted a periodicity search using the Lomb-Scargle periodogram (Scargle 1982); Figure 2. We find a signal at a period of 58.8 min, exactly half of the previously reported period. Surprisingly, no obvious signal is detected at the harmonic of 117.6 min, even though three cycles at that periodicity fit into the observation. The 58.8-min period is the only peak in the periodogram above the critical level of about 16 that corresponds to a false alarm probability of 0.01. Note that the false alarm probability does not take into account the flux density errors of the light curve.

We also detect 2M0036+18 with a flux density of 144 ± 22 μJy, similar to previous detections (§2). No significant variability was detected in the light curve.

3.2. *VLBA observations*

TVLM513–46 is detected with the VLBA, the first such detection of any ultracool dwarf. To locate the source in a data set using the inner seven VLBA antennas we shifted the phase center of the *uv* data to the nominal VLA position and created a map covering $0.2'' \times 0.2''$, encompassing the VLA position uncertainty (1σ = 45 mas). We find a single robust source at the 8σ significance level, which persists with changes in the imaging parameters and source detection routines (AIPS SAD and JMFIT). The source is located 46 mas (i.e., 1σ) from the nominal VLA position. We therefore identify this source as the VLBA counterpart of TVLM513–46 and shift the phase center to this position for subsequent analysis. The source is located at a position of RA=15$^{\rm h}$01$^{\rm m}$08.1647696$^{\rm s}$ ($\pm$0.0000077 s), Dec=+22°50′01.63968″ ($\pm$0.00011″), where the errors are statistical only (Figure 3).

With a synthesized beam size of 2.5×2.3 mas (PA = 26°) the source appears to be unresolved; it has a peak brightness of 420 ± 48 μJy beam^{-1} and an integrated flux density of 360 ± 75 μmJy (the VLA and VLBA fluxes overlap at the 2σ level). At the distance of TVLM513–46, the beam size corresponds to a spatial resolution of about 0.026 AU, or about 50 times larger than the expected radius of TVLM513–46.

To follow up on this detection with an increased angular resolution, we added the outer VLBA antennas located on Mauna Kea and St. Croix. The resulting synthesized beam size is 1.7×0.9 mas (PA = 6°). At this resolution, the S/N ratio decreases, and the peak brightness of TVLM513–46 is 230 ± 47 μJy beam^{-1}, and its integrated flux density of 540 ± 150 μJy has a larger error bar since the source no longer appears to be well-described by a single unresolved Gaussian component. Instead, it appears asymmetric and resolved (Figure 4). This indicates a marginally resolved source on the longest baselines, but the significance is too low to warrant a firm conclusion. The synthesized beam corresponds to a source size of about 20 stellar radii, larger than expected for the magnetic field scale (e.g., Linsky & Gary 1983). We therefore conclude that if TVLM513–46 is indeed resolved, then this likely indicates a binary system with two radio-emitting sources and a projected separation of about 1 mas. In this case, since radio emission has only been detected to date from objects with spectral type earlier than L3.5 (Berger 2006), the binary would likely be close to equal mass.

We note that 2M0036+18 was not detected in the VLBA data due to insufficient sensitivity.

4. IMPLICATIONS OF THE VLBA DETECTION

Since TVLM513–46 is unresolved on a scale of about 2.5 mas, we can place a firm lower limit on the brightness temperature of its quiescent emission of $\gtrsim 4\times10^5$ K. This is not sufficiently high to *directly* rule out thermal emission (e.g., Dulk 1985). To constrain the brightness temperature to values above 10^7 K, indicative of non-thermal emission, the angular resolution will have to be $\lesssim 0.4$ mas. We note that other considerations (expected size of the magnetic field, radio spectral index) point to non-thermal emission (e.g., Osten et al. 2006).

The sub-milliarcsecond astrometry of TVLM513–46 that is available thanks to its detectability with the VLBA underscores the potential for a VLBI astrometric companion search. Since TVLM513–46 is already at the stellar/sub-stellar transition, such a companion would be a sub-stellar object (brown dwarf or planet). Bower et al. (2009) have recently used such VLBA astrometry to search for companions to nearby early-M dwarfs. They detected five M dwarfs with spectral types M1-M5 in one to three epochs with the VLBA down to a 5σ sensitivity limit of about 0.5 mJy. Their astrometric residuals compared to optical measurements of the parallax and proper motion were about 0.2 mas, similar to the astrometric accuracy we achieved here for TVLM513–46.

The signal-to-noise ratio of our detection only allows us to search for an astrometric shift during the 7-hour observation when separately imaging the first and second halves of the data set. Using data from the inner 7 VLBA antennas we find a positional difference of 0.47 ± 0.37 mas, consistent with no significant shift. We note that the expected maximum astrometric shift (equal-mass companion) for an orbit of a few hours is about 0.2 mas, indicating that VLBA observations alone (with $1\sigma\approx0.2$ mas) cannot detect the presence of such a companion at the brightness level of TVLM 513–64. However, more sensitive combined VLBA+GBT observations may provide the required signal-to-noise ratio to probe the presence of an equal-mass companion in a few-hour orbit (corresponding to a separation of $\sim$ few stellar radii). Moreover, if TVLM513–46 is indeed a roughly equal mass binary with a projected separation of about 1 mas ($\gtrsim 1$ d orbit) we expect an easily detectable astrometric signature of ~ 1 mas on a 1 d timescale.

Equally important, a planetary-mass companion to TVLM513–46 can be detected on longer timescales, since a wider orbit leads to a larger astrometric signal. In Figure 5 we plot the maximum reflex motion induced by a companion orbiting TVLM513–46 with a range of masses ($1-40$ M$_J$) and orbital periods (0.1 d to 1 yr). We find that at $3\sigma\approx0.6$ mas for VLBA observations similar to the one presented here, we can detect a 10 M$_J$ companion with an orbital period of $\gtrsim 15$ d ($\gtrsim 0.06$ AU), or a 2 M$_J$ companion with an orbital period of $\gtrsim 0.5$ yr ($\gtrsim 0.3$ AU). Using the combined VLBA+GBT, with an expected astrometric uncertainty of $3\sigma\approx0.3$ mas (due to a higher signal-to-noise ratio and a higher fraction of longer baselines), we will be able to detect a 1 M$_J$ planetary companion in a $\gtrsim 0.5$ yr orbit. We note that these limits are appropriate for the case where TVLM513–46 is a single star. If the object is an equal mass binary, as may be indicated by the results of direct imaging, the search for planetary-mass companions will be more challenging.

5. CONCLUSIONS AND FUTURE PROSPECTS

Using high angular resolution radio VLBI observations, we clearly detect the ultracool dwarf TVLM513–46 on an unprecedented small scale of about 2.5 mas or about 50 stellar radii. The source is unresolved on this scale, but it may be marginally resolved on a ~ 1 mas scale when using the longest VLBA baselines, although the S/N ratio is low. Given the corresponding physical scale of about 20 stellar radii, this may point to a binary system with two radio-emitting sources in a $\gtrsim 1$ d orbit.

Beyond the possibility of a spatially resolved binary, a search for an astrometric shift in the position of the source due to the gravitational influence of a close companion yields a 3σ limit of $\lesssim 0.6$ mas, about 3 times larger than the expected shift for an equal-mass companion in a few-hour orbit. Since we lost the phased-VLA and GBT data, we expect that future VLBI observations will provide the requisite astrometric accuracy to search for an equal-mass companion in such a tight orbit. These future observations will also allow us to determine whether the marginally-resolved emission from TVLM513–46 is indeed due to an equal mass companion with a projected separation of about 20 stellar radii. If this is indeed the case, the expected maximum reflex motion is about 1 mas, easily detectable with VLBA+GBT observations that span several days.

Equally important, the fact that TVLM513–46 is detected with the VLBA opens the possibility to astrometrically search for a planetary-mass companion with a $\gtrsim 10$ d orbit. Monitoring of TVLM513–46 with the VLBA or VLBA+GBT on timescales of days to months to years will allow us to probe the existence of companions with masses of $\sim 1-10$ M$_J$ and with orbits of ~ 15 d to ~ 1 yr. These observations may lead to the first detection of an extrasolar planet via radio astrometry.

Thus, the use of VLBI observations opens up a wide companion parameter space for TVLM513–46, with detection via direct imaging for a roughly equal-mass radio-emitting companion down to a scale of ~ 20 stellar radii, and detection via reflex motion on scales as small as a few stellar radii for an equal mass companion, and scales of $\gtrsim 0.1$ AU for a planetary mass companion. This first VLBA detection also paves the way for similar observations of known and future radio-emitting ultracool dwarfs in search of companions.

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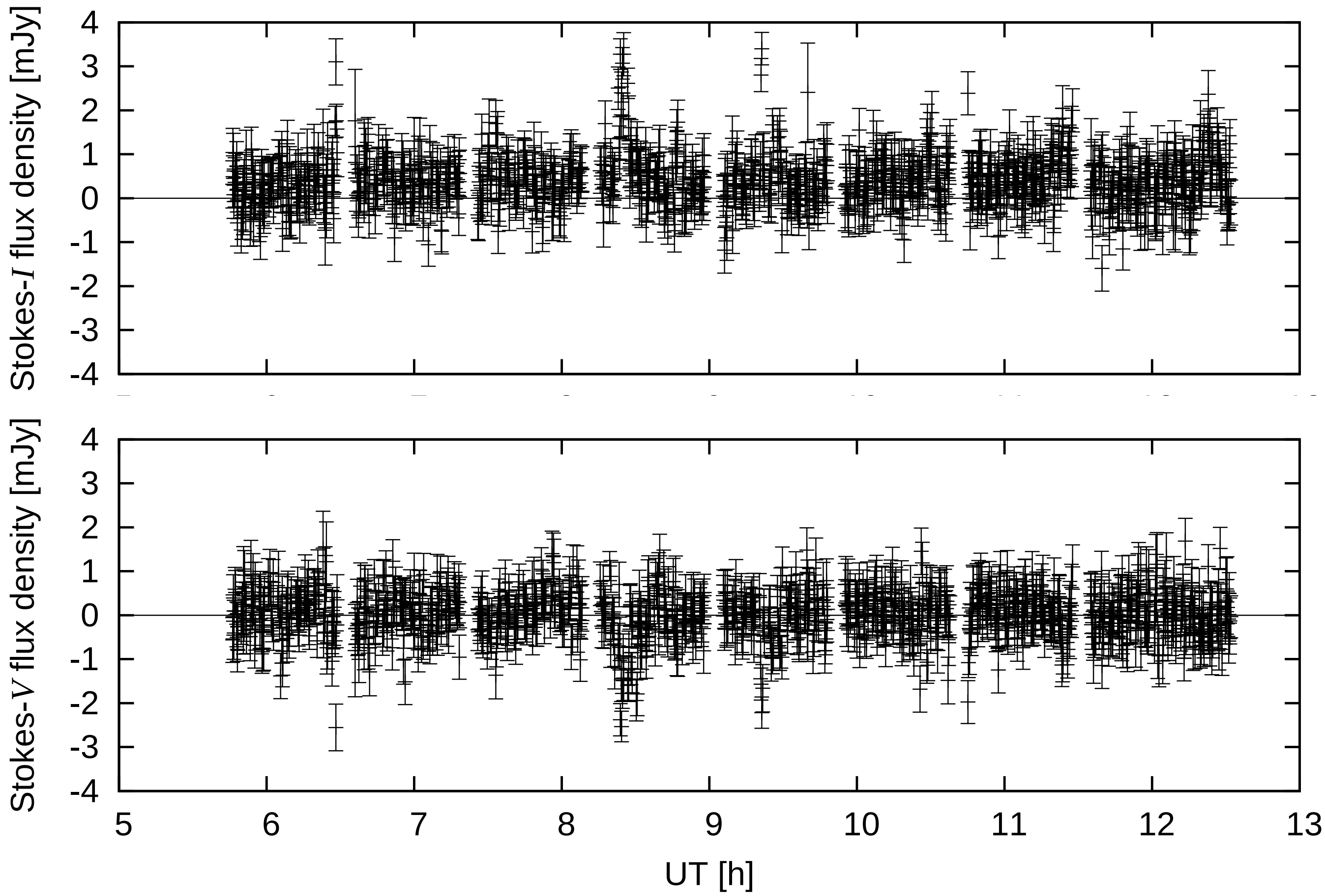

FIG. 1.— VLA 8.5 GHz light curve of TVLM513–46 with a time resolution of 10 s. The upper panel shows the total intensity (Stokes *I*), and the lower panel shows the circularly polarized flux (Stokes *V*); negative values indicate left-handed circular polarization. For better visibility, all points that have error bars more than three times larger than the average error were discarded.

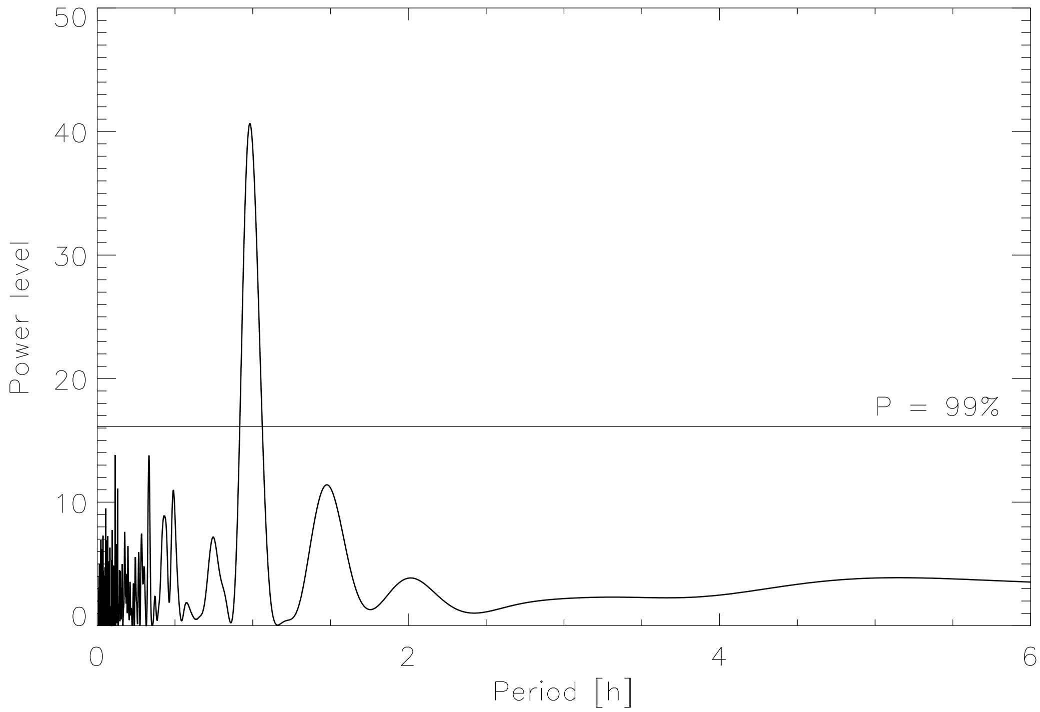

FIG. 2.— Lomb-Scargle periodogram for the VLA 8.5 GHz light curve of TVLM513–46. The horizontal line denotes the power level corresponding to a false alarm probability of 0.01. We find a significant peak at a period of 58.8 min.

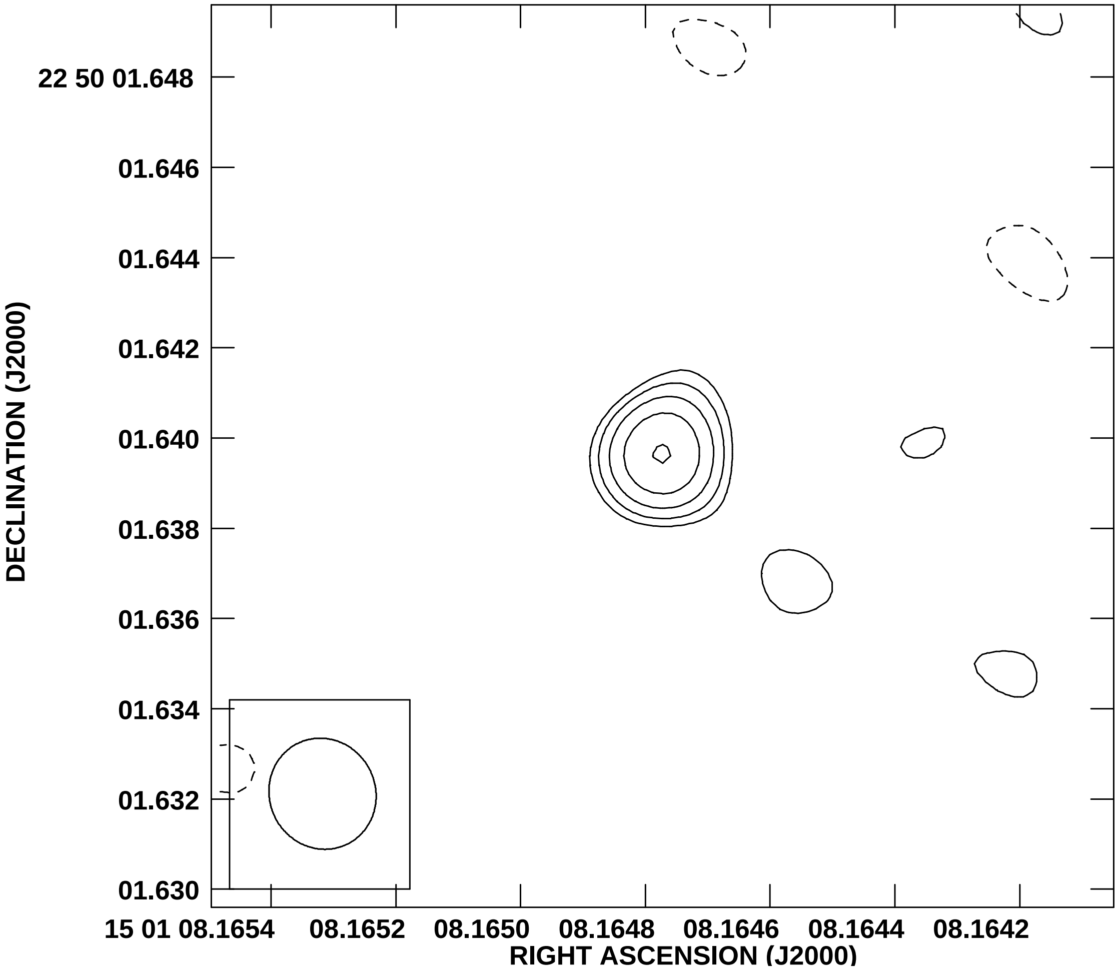

FIG. 3.— VLBA detection of TVLM513–46 using the inner seven antennas. Contour lines are –2,2,2$\sqrt{2}$,4,4$\sqrt{2}$,8 σ, where σ = 48 μJy; the synthesized beam size is indicated in the lower left corner.

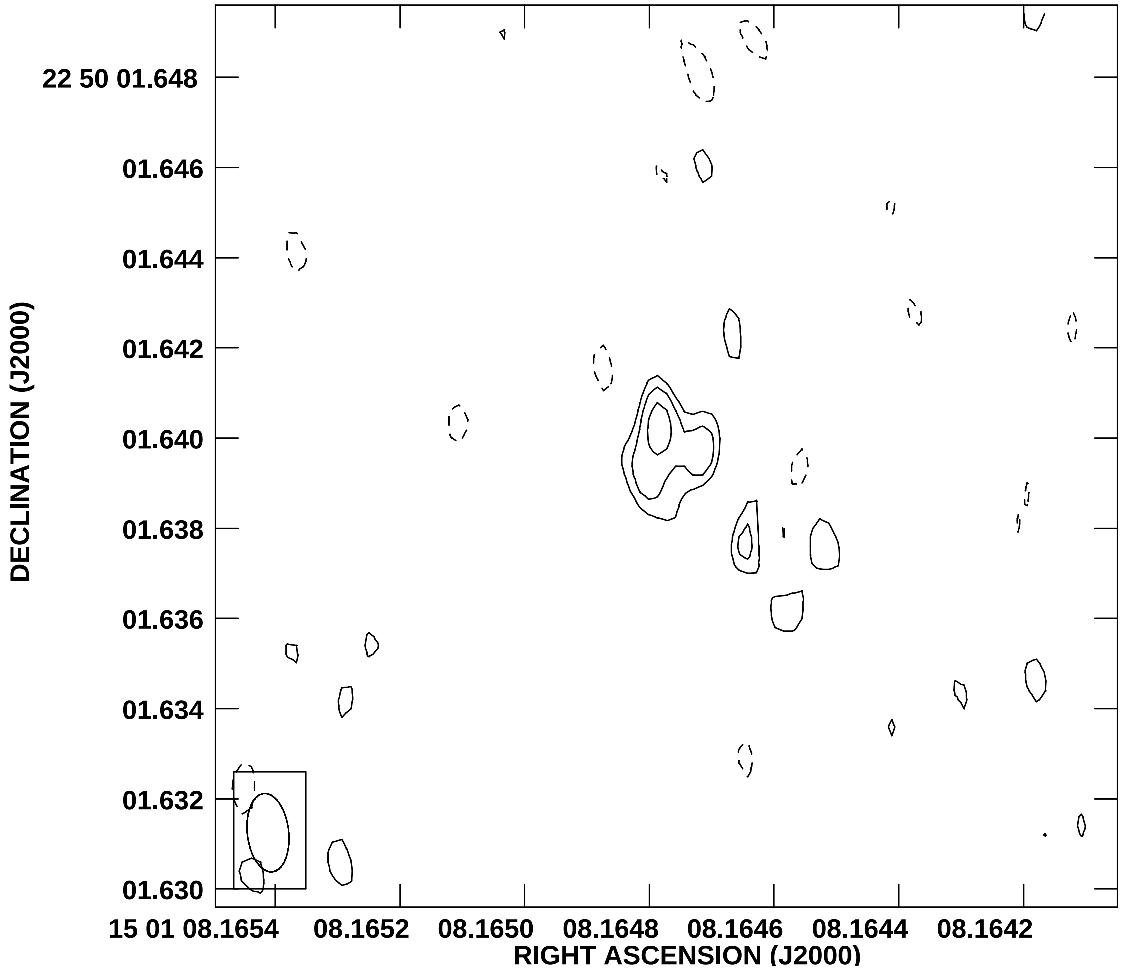

FIG. 4.— VLBA detection of TVLM513–46 using the entire VLBA (minus Hn). Contour lines are $-2,2,2\sqrt{2},4,4\sqrt{2}\,\sigma$, where $\sigma = 50\ \mu$Jy; the synthesized beam size is indicated in the lower left corner. The source appears to be marginally resolved and asymmetric at this resolution, possibly indicating that TVLM513–46 is a roughly equal-mass binary system.

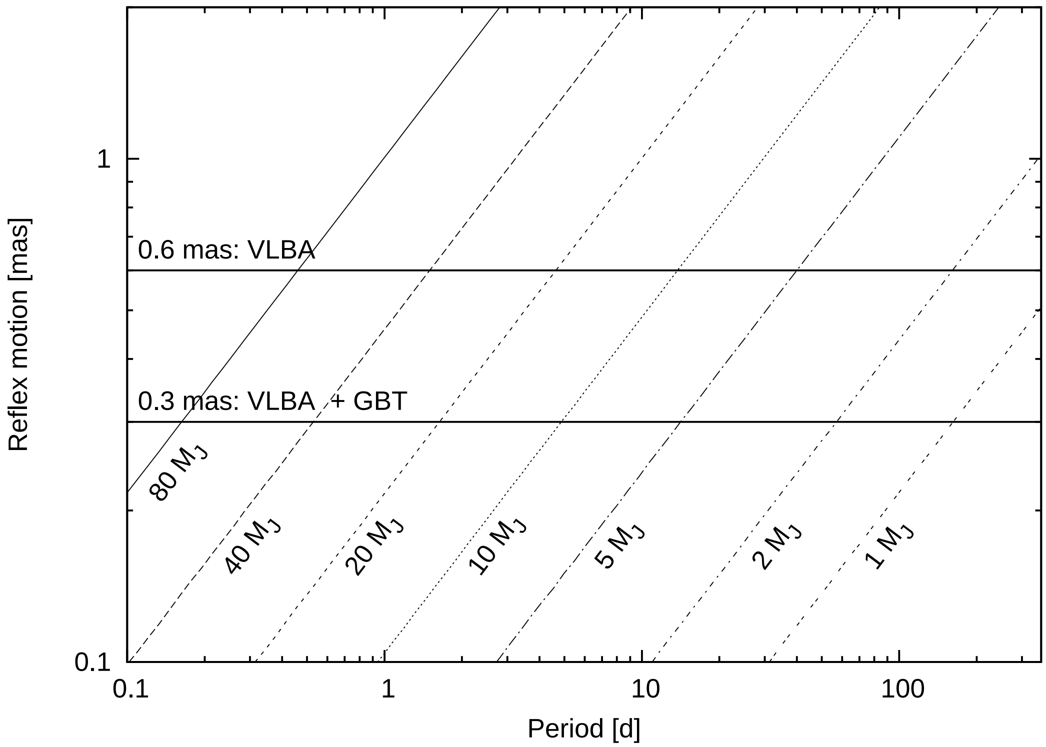

FIG. 5.— Predicted maximum reflex motion for companions with masses of 80, 40, 20, 10, 5, 2, and 1 M_J (left to right), as a function of the corresponding orbital period, assuming that TVLM513–46 is a single star. While a single observation with the VLBA+GBT has the potential to directly detect a radio-emitting (and hence roughly equal mass) companion down to a scale of ~ 1 mas (corresponding to a ~ 1 d orbit), observations spaced over a year can detect a sub-stellar companion down to a few Jupiter masses via reflex motion. If TVLM513–46 is indeed an equal-mass resolved binary on a milliarcsecond scale, then we should be able to further constrain the system with the detection of astrometric reflex motion, expected to be at a level of about 1 mas.